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Reliability Prediction of Board-Mounted Power Modul s

Introduction

The reliability figure of merit most often used for electronic equipment is mean time between failures (MTBF). This is not an exactly known value for an individual piece of equipment, but is a statistical estimate for the equipment population. Suppliers usually estimate MTBF using a prediction methodology based on reliability data for the individual components in the equipment. Component data comes from several sources: device life tests, failure analysis of earlier equipment, device physics, and field returns.

The best-known reliability prediction methodology is MIL-HDBK-217, but other methods are available. The telecommunications industry commonly uses Bellcore Technical Reference TR-332, *Reliability Prediction Procedure for Electronic Equipment* (RPP). In addition, many companies have developed methodologies adapted to their own products and experience. The *Reliability Information Notebook* (RIN) is an example of this. These prediction methods share several assumptions:

- During the useful life of a piece of equipment, the failure rates of the individual components are constant.
- The base failure rate for a component is its failure rate at a reference temperature and electrical stress. The base failure rate of a component is multiplied by thermal and electrical stress acceleration factors to find its failure rate in the equipment.
- The failure rates of individual components, adjusted to use conditions, are summed to find the failure rate of the equipment.

Bellcore RPP and Tyco RIN employ the same models for acceleration factors for temperature and electrical stress. The primary differences between the two methods are the component base failure rates, the reference level for electrical stress, and parameter values in the models such as activation energy. RIN base failure rates are determined primarily from analysis of field returns for Tyco manufactured equipment. Thus, the components involved are either manufactured by Tyco or purchased according to Tyco purchase specification. Purchase specifications and supplier and component qualification processes give Tyco a measure of control of the quality and reliability of the commercial devices bought.

Tyco Methodology

The following outlines the methodology employed to predict the reliability of Tyco board-mounted power modules. Because of the investment in determining component failure rates from field data, the base failure rates published in the most recent issue of the RIN (7th edition) are considered proprietary. However, the concepts and models, and RIN 5th edition component failure rates have been published as the *AT&T Reliability Manual*[1]. Component failure rates in the RIN are given in units of FITs, where 1 FIT = 1 failure in 10^9 hours. Component base failure rates are given at 40 °C, 25% electrical stress. The failure rate for the module at a given condition of temperature and electrical stress is calculated by the following:

$$\lambda_m = \sum_{i=1}^{n} A_{Ti} S_i \lambda_i$$

where:

n	=	number of components in the module
A_{Ti}	=	temperature acceleration factor
S_i	=	electrical stress acceleration factor
λ_i	=	base failure rate for the i^{th} component

1. D.J. Klinger, M.A. Mendez, Y. Nakada, *AT&T Reliability Manual*, Van Nostrand Reinhold, New York, NY, 1990, ISBN 0-442-31848-0.

Tyco Methodology (continued)

The temperature acceleration factor for a component is given by:

$$A_{Ti} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{ref}} - \frac{1}{T_{op}}\right)\right]$$

where:

- E_a = activation energy in electron volts (eV)
- k = Boltzman constant, $8.6 \cdot 10^{-5}$ eV/K
- T_{ref} = reference temperature, 313 K (40 °C)
- T_{op} = operating temperature in K (273 + °C)

The electrical stress acceleration factor for a component is given by:

$$S_i = \exp[m_i(P_{op}^i - P_{ref})]$$

where:

- m_i = stress parameter
- P_{op}^i = percent of rated electrical stress applied for the ith component
- P_{ref} = reference percent stress (25%)

One drawback of the original RIN method is the use of ambient temperature for the temperature acceleration. This measure of temperature does not take into account the possibility of different thermal performance of various components and packaging techniques. In order to circumvent this problem, we use individual component temperatures for the temperature acceleration calculation:

$$T_{op}^i = T_{case}^{PM} + \Delta(T_{op}^i - T_{case}^{PM})$$

where:

- T_{case}^{PM} = case temperature of the power module,
- $\Delta(T_{op}^i - T_{case}^{PM})$ = temperature rise above T_{case}^{PM} for the ith component (obtained from thermocouple measurement)

The original RIN method is further modified as follows to make it better suited for board-mounted power modules (BMPM). We first calculate the failure rate of the power module, λ_m, for a set of conditions. Then the regression method is employed to obtain the parameter values for the power module, E_a^{PM}, m^{PM}, λ_b^{PM}. By using these fitting parameters, we can treat the power module as a component. We consider load current to be the electrical stress for the module.

(Step 1)

Obtain λ_m for a set of conditions

(Step 2)

Fit $\lambda^{PM} = A_T^{PM} S^{PM} \lambda_b^{PM}$ to λ_m for the set of conditions

(Step 3)

Obtain E_a^{PM}, m^{PM}, λ_b^{PM}

(Step 4)

Obtain $\lambda^{PM} = A_T^{PM} S^{PM} \lambda_b^{PM}$ using the fitting parameter values above

where:

$$A_T^{PM} = \exp\left[\frac{E_a^{PM}}{k}\left(\frac{1}{T_{ref}^{PM}} - \frac{1}{T_{case}^{PM}}\right)\right]$$

temperature acceleration at use module case temperature with respect to T_{ref}^{PM} = 40 °C

$$S^{PM} = \exp[m^{PM}(P_{op}^{PM} - P_{ref}^{PM})]$$

stress acceleration at use load (P_{op}^{PM} in %) with respect to P_{ref}^{PM} = 25% load

λ_b^{PM}: Module base failure rate at 40 °C module case temperature, 25% load (as obtained from the regression procedure)

The MTBF in hours is then given by:

$$\text{MTBF[hours]} = \frac{1 \cdot 10^9}{\lambda^{PM}[\text{FITs}]}$$

as a function of T_{case}^{PM} and P_{op}^{PM}.

Tyco Methodology (continued)

Exampl :

The FE150A power module will be used to demonstrate the RIN methodology. Table 1 at the end this technical note is an annotated FE150A bill of materials that gives full-load temperature rise of each component with respect to the module case, the maximum rated temperatures and electrical stress, as well as the worst-case electrical stress at nominal line voltage.

The column labeled ΔT_{j-c} gives the temperature rise of the component with respect to the module case temperature. This temperature difference is taken from the junction for semiconductor devices and from the component case for passive devices. Note that the FE150A data sheet includes a case temperature reference location. Zero in this column indicates the assumption that the component junction or case temperature is at the module case temperature.

The column label T_{max} indicates the maximum rated case temperature for passive components and the maximum rated junction temperature for semiconductor components.

The column labeled Rated ES gives the specified rating for the component, and the column labeled Work ES gives the electrical stress at the operating condition as follows:

Component	Stress
Capacitors	Voltage
Diodes (except zener)	Reverse voltage
Zener diodes	Power dissipation
Transistor	c-e or d-s voltage
Resistor	Power dissipation
Optoisolator	Detector bias voltage

Zero in the Work ES column means that the component is operated at ≤25% of rating.

The Tyco RIN lists the parameter values by component type, i.e., the activation energy, E_a, and stress parameter, m, as well as the component base failure rates.

The temperature and electrical stress information in the table is used to calculate acceleration factors. For example, the junction of CR6 is 31 °C hotter than the case of the FE150A. Using E_a = 0.4 eV for CR6, A_T = 3.8 at module case temperature of 40 °C:

$$A_T = e^{\frac{0.4}{8.6 \cdot 10^{-5}}\left[\frac{1}{313} - \frac{1}{(313+31)}\right]} = 3.8$$

Capacitor C2_3 is rated at 75 V and has 50 V stress in typical applications. The electrical stress acceleration factor for 67% applied stress is 11.9:

$$S = e^{0.059(67-25)} = 11.9$$

where m is 0.059 for a ceramic-chip capacitor following the Tyco RIN listing.

The temperature and electrical stress acceleration factors are calculated for each component in the module, and are multiplied by the base failur rate. The products are summed to determine the module failure rate at that operating condition. Computer programs perform these calculations for several operating conditions, and perform curve fitting (regression method) to determine the overall activation energy, E_a^{PM}, stress parameter, m^{PM}, and base failure rate for the module, λ_b^{PM}. For the FE150A, the base failure rate is 345 FITs, the activation energy is 0.383 eV, and the stress parameter is 0.00473.

If the operating environment for the FE150A is known, one can apply this information to calculate the predicted reliability under these conditions. For example, assume an application that uses the FE150A at 80% of full load (24A), maximum cabinet temperature of 35 °C, with 200 lfm across each board in the system. Also assume that the FE150A has a 0.5" high heat sink, giving a module case-to-ambient thermal resistance of 1.2 °C/W in a 200 lfm air stream[1]. Assuming 81% conversion efficiency, the FE150A dissipates about 23 W at 24 A_{out}; thus the module case temperature rise is 23 W * 1.2 °C/W = 27.6 °C. Therefore, the maximum module case temperature is 62.6 °C in this environment. The temperature acceleration factor is calculated as:

$$A_T^{PM} = e^{\frac{0.383}{8.6 \cdot 10^{-5}}\left[\frac{1}{313} - \frac{1}{(273+62.6)}\right]} = 2.6$$

The electrical stress acceleration factor is calculated as:

$$S^{PM} = e^{0.00473(80-25)} = 1.3$$

1. For additional information regarding thermal management, refer to the *Thermal Management for High-Power Board-Mounted Power Modules* Technical Note, TN97-009EPS.

Tyco Methodology (continued)

The failure rate at these conditions is 2.6 • 1.3 • 345 = 1170 FITs. Therefore, the MTBF is given as:

$$\text{MTBF} = \frac{10^9}{1170} = 858{,}000 \quad \text{hours}$$

Figure 1 shows the MTBF versus module case temperature for three different load levels.

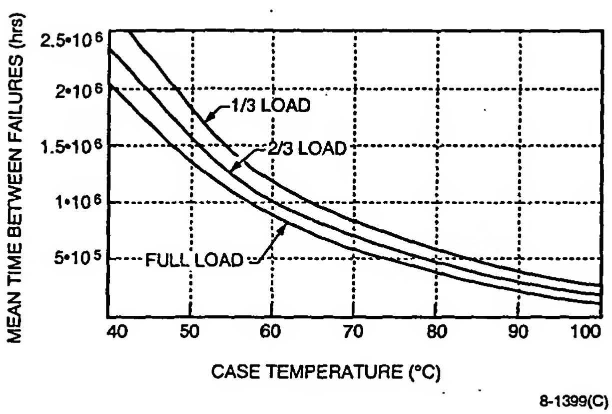

Figure 1. MTBF in Hours vs. Case Temperature for 1/2, 2/3, and Full Output Power for the FE150A

The methodology for predicting the reliability of Tyco's BMPM is detailed above. The resulting information enables users to see the effect of design decisions and system environment on system reliability calculations.

Tyco Methodology (continued)

Table 1. FE150A Bill of Materials

Qty	Ref	Type	Description	Value	ΔTj – c	Rated ES	Work ES	Tmax
13	C10	cap	Ceramic-chip-NPO	470 pF	0	50	5	125
9	C33	cap	Ceramic-chip-X7R	4700 pF	0	50	5	125
1	C13	cap	Ceramic-chip-X7R	0.1	0	50	13.5	125
1	C17	cap	Ceramic-chip-X7R	0.1	0	50	12.5	125
1	C18	cap	Ceramic-chip-X7R	0.1	0	50	24	125
3	C1_1	cap	Ceramic-chip-NPO	0.47	0	75	50	125
6	C2_3	cap	Ceramic-chip-NPO	0.47	7	75	50	125
2	C3_2	cap	Ceramic-chip	1000 pF	0	200	120	125
7	C4_1	cap	Ceramic-chip-NPO	0.47	16	75	5	125
1	C53	cap	Ceramic-chip-NPO	1000 pF	0	50	12.5	125
1	C5_5	cap	Ceramic-chip-NPO	0.47	10	75	5	125
2	C6	cap	Ceramic-chip-NPO	1000 pF	45	50	30	125
2	C80	cap	Ceramic-chip	3300 pF	0	500	25	125
2	C16	cap	Chip-solid-tantalum	1.5	0	25	12	125
1	C30	cap	Chip-solid-tantalum	1.5	0	25	1.3	125
4	C5_1	cap	Chip-solid-tantalum	47	10	8	5	125
5	CR10	dio	General-purpose-70 V-200 mA	NA	0	70	0	175
3	CR16	dio	General-purpose-70 V-200 mA	NA	0	70	2	175
3	CR40	dio	General-purpose-70 V-200 mA	NA	0	70	14	175
1	CR13	dio	General-purpose-30 V-200 mA-dual-com	NA	0	30	11	175
5	CR34	dio	Zener(gp)-si	3.3	0	0.35	0	175
1	CR6	dio	Rectif-40 V-80 A-com-cath-schott	NA	31	40	20	175
1	IC10	ic	Linear-plastic-100-300 trans	NA	12	0	0	150
2	IC20	ic	Linear-plastic <100 trans-dual-op amp	NA	0	0	0	150
1	IC30	ic	Linear-plastic <100 trans	NA	0	0	0	150
1	L1	ind	Power.inductor-surf-mnt	NA	0	0	0	130
1	L2	ind	Power.inductor	NA	30	0	0	130
1	L3	ind	rf.fixed bead	NA	15	0	0	130
2	Q1	trns	fet.switch.plastic, 18 A	NA	11	200	150	150
1	Q10	trns	pnp-20 V-1 A-1.5 W	NA	0	20	11	150
1	Q12	trns	npn-darl-80 V-0.5 A-1.5 W	NA	0	80	8	150
1	Q13	trns	npn-45 V-0.2 A	NA	0	45	12	150
1	Q14	trns	fet switch plastic 200 V-4 A	NA	0	200	120	150
1	Q15	trns	npn-50 V-1.0 A	NA	0	50	12	150
1	Q16	trns	pnp-45 V-0.2 A	NA	0	45	5	150
6	Q30_2	trns	npn-50 V-1.0 A	NA	0	50	0	150
1	Q68	trns	npn-50 V-1.0 A	NA	0	50	13.5	150
2	R20	res	Chip-film	51.1K	0	0.13	0.03	125
58	R30	res	Chip-film	1K	0	0.13	0	125
5	R18	res	melf	1	0	0.25	0	150
9	R1	res	melf	20.5	0	0.25	0.1	150
1	T1	trnf	Power-transformer	NA	45	0	0	130
1	T2	trnf	Current-transformer-surf-mnt	NA	13	0	0	130
1	T3	trnf	Transformer-surf-mnt	NA	27	0	0	130
1	U30	opto	Dual-tran-detect-70 V-0.1 A-2500 Visolation	NA	14	70	5	150

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